Effects on Scour for Different Foundation Geometry of Compound Circular Bridge Piers

Anjali Sharwan, P.T. Nimbalkar

ABSTRACT: ***This experimental study examines the variation of scour depth with time of Clearwater scour condition around compound circular bridge piers for steady flow conditions. Most of the circular bridge piers are resting on the bigger diameter caissons known as the compound circular bridge piers and are widely used in India for construction of road and railways bridge across the rivers. In past studies, it has been observed that most bridge failure occurs because of scouring due to flowing water around a bridge pier across a river. Most of the past studies were done on the uniform bridge pier and a very few studies have been done so far on scouring around non-uniform bridge piers. Estimation of scour depth is required for the economical and a sound design of bridge pier foundation. In present study, an experimental investigation has been done in a tilting flume for computation of rate of change of depth of scour with time at two different models of compound circular bridge piers by varying the foundation top position with respect to level of bed, i.e., 1. The foundation top at the level of bed, and 2. The foundation top below the level of bed (viz. 10mm, 20mm, 30mm and 40mm) for uniform sediments.***

KEYWORDS**:** ***Scour depth, Compound Circular Bridge pier, Clearwater, Uniform sediment.***

I. INTRODUCTION

Scouring around a bridge pier is a three-dimensional complex phenomenon and therefore mostly the bridge failure occurs because of local scour. The bridge failures due to extreme local scour during floods requiring much effort to hydraulic engineers. The obstructions like spurs, abutments, bridge piers and guide banks, etc. are some common hydraulic structures, which significantly changes the flow pattern of the stream around the hydraulic structures. The process of scouring occurs because of high shear stress and sediment transport around bridge piers. It is always represented in the graphical form by plotting the maximum depth of scouring versus the time and therefore it is a time-dependent process. It is very difficult to calculate the correct maximum scour depth in the given time because of the complex three-dimensional phenomenon. The mechanism of local scour occurs when there is any obstruction like pier or abutment across the river, the one-directional flow change into three- dimensional flow as the water flows downward at the front side of the bridge pier, vortices are formed at the bed of the river and the flow starts to accelerate around the nose [1-2]. This phenomenon will results in the vortex formation at the toe of the pier called as horseshoe vortex and the formation of vortex on the downstream side of the bridge pier are known as the wake vortex. Horseshoe vortex is the principle vortex that helps in transporting the sediment particle from the vicinity of the bridge pier [3]. With an increase in scour depth around a pier the intensity of horseshoe vortex decreases and automatically the rate of scouring also decreases [4]. The intensity of horseshoe vortex acts mainly on the front side of the pier therefore, depends upon the flow condition, size, and shape of bridge pier and properties of sediment particles. The intensity of wake vortex depends upon the geometry of bridge pier and flow characteristics and decreases in the downstream face of the pier and the eroded sediment particles get deposited at downstream of the bridge pier. Compared to horseshoe vortex, the intensity of wake vortex is less. Thus maximum scouring occurs at the front side of the bridge pier because of downward flow effect on stream bed [3]. Number of investigations have been done on developing relationships for maximum scour depth and time, resulting in a large amount of literature review is available on the local scouring for the bridge piers. The various relationships have been given by many researchers to estimate the bridge scour in clear water flow condition and live bed flow condition. Through laboratory experimentations within the vicinity of scour hole around the circular uniform bridge pier the flow pattern has been studied by many researchers [5-8]. These past studies have mostly emphasized on scouring around piers which have a uniform cross-section along with their height and did not consider the foundation geometry effect on scouring. Nowadays, compound circular bridge piers are used in practices in India which are placed on the bigger diameter of circular foundation [9].Many researchers have also investigated that foundation geometry significantly affects the local scour and all the past studies are carried out with uniform sediments and for clear water conditions [10-12]. The mechanism of scouring have been studied to know the phenomenon responsible for local scour.

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The objective of this present study is:

- To develop relationships for the maximum depth of scour for compound bridge pier.
- To study the variation of scour depth w.r.t. uniform sediments around compound bridge pier.
- To study the effects on scour depth around compound bridge pier w.r.t position of the foundation top and river bed level.
- To study the effects of pier foundation ratio on scour depth.

II. EXPERIMENTATION

Experimental works were performed in the Fluid Mechanics laboratory of the Civil Engineering Department of Bharati Vidyapeeth (Deemed to be) University College of Engineering, Pune, Maharashtra, India.

A. Flume

A tilting flume having a length of 10m, 0.30m width and 0.55m depth was used to conduct the experiments for the present study. The flume has a working section of 1.0m length, 0.30m width, and 0.10m depth which was filled with desired uniform sediment to a uniform depth of 0.10m and the length of sediment bed 1.5m and 0.30m, in width. The test section of the flume was located 4.5m from the upstream side of tilting flume. The acrylic false bed was made at an elevation of 0.10m at the base of flume throughout the flume length except test section to provide the same elevation as in bed level. The measurement of flume discharge was done with calibrated V notch placed in the return channel. The flume flow depth was measured with vernier pointer gauge. An adjustable flow control valve was located at the flume end to control the flume flow depth. The flume in the laboratory was connected to the supply of water system. The flume slope and the flume test section location were made in such a way that the flow developed fully before reaches the test section. Photographic view of flume in the Figure 1.

Figure 1. View of Tilting Flume

B. Sediment sample

Non cohesive locally available river bed sand was used as a sediment sample in the experimentation work. The sieve analysis of sand layer was shown in the form of particle size distribution curve as shown in Figure 2. Properties of sediment sample are as follows:-

- Sediment type = Uniform sand
- Mean size of sediment, d_{50} = 0.8mm
- Geometric Standard Deviation, σg = 1.118
- $\sigma g = (d_{84}/d_{16})^{1/2}$

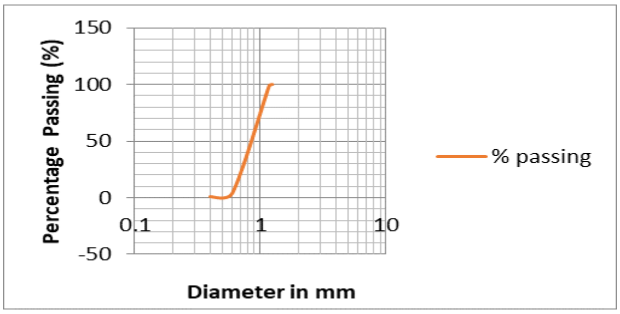

Figure 2. Particle size distribution curve for uniform sediments (σg = 1.118, d_{50} = 0.8mm)

C. Models of compound piers

The models of compound circular bridge pier were made up of PVC pipes. Figure 3 shows the models of circular nonuniform bridge piers used in the experimental study. The pier diameter was kept same for two different models, only the foundation diameter was varying and dimensions for pier models used in experimentation is shown in the form of table I.

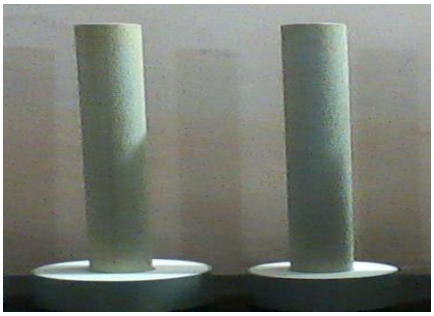

Figure 3. Photograph showing two models of bridge pier

Table I. Dimensions for pier models used for experimentation work

Name of the model	Diameter of pier in mm	Diameter of foundation in mm
Model 1 (compound circular pier)	32	75
Model 2 (compound circular pier)	32	90

D. Pre experimental data calculations

In this study Clearwater scours conditions were maintained during experimental work and V/V_c ratio is less than Unity.
V = Approach velocity of flow and V_c = critical flow velocity, calculated by using Shield method [13] for uniform sediments.
V is the approach flow velocity calculated from the known discharge and depth of flow for a single discharge value. During the experimentation work, discharge is adjusted by the inlet gate and outlet gate. The discharge can be calculated from the V notch equation as given below,

$$Q = \frac{8}{15}\sqrt{2g}C_d H^{\frac{5}{2}}$$

(1)

$C_d = 0.611 + 0.08\frac{H}{h}$ Or Cd = 0.61 (2)

Depth of flow is measured in the tilting flume for particular discharge values and the approach velocity of flow is calculated by using the continuity equation given below,

V = Q/A (3)

$A = (B \times D)$ (4)

The ratio V/Vc is the measure of flow intensity and determines whether sediment transportation occurs on the channel bed. For clear water flow condition $V/V_c < 1$.

Shields chart for threshold condition is used for uniform sediments in the water and the shear velocity u*c corresponding to d_{50} is obtained. The shear velocity u*c is calculated by mean shear velocity V_c in the form of a logarithmic velocity flow profile given in equation (5).

$$\frac{V_c}{u_{*c}} = 5.75\ log\left(5.53\ \frac{D}{d_{50}}\right) \quad (5)$$

Table II shows the experimental data for uniform sediment and Table III shows the experimental condition for test series on tilting flume for uniform sediment.

Table II. Experimental data for uniform sediment

Variable	Quantity
Geometric standard deviation, σ_g	1.118
Median size of sediment, d_{50} (mm)	0.8 mm
Flow depth, D (mm)	110 mm
Average approach flow velocity (calculated), V (m/s)	0.35212 m/s
Critical flow velocity of sediment motion (calculated), V_c	0.3644 m/s
Footing elevation w.r.t. bed level, Y (mm)	10 mm, 20 mm, 30 mm, 40 mm, and the same as the bed level

Table III. Experimental condition for test series on tilting flume for uniform sediment

D (m)	B (m)	d_{50} (m)	u_{*c} (m/s)
0.11	0.30	0.0008	0.022
V_c (m/s)	**Q (m^3/s)**	**V (m/s)**	**V/ V_c**
0.3644	0.01162	0.35212	0.96630

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The scouring around a bridge pier is a time-dependent process. In the present study various analysis has been done for the rate of change of scour depth with time for uniform sediments for two models of compound circular bridge pier at different positions of the foundation top of a pier with respect to the sand bed level in Clearwater scour condition. The experimental observations were taken continued until the equilibrium scour depth is reached, and the rate of change in the scour depth becomes insignificant [14]. Scour depths were measured with the help of vernier pointer gauge for 5 hours i.e. 300 minutes duration and scour depths were noted down at every 20 minutes of interval. Figure 4 to Figure 8 shows the graphical representations of scour depth vs. time for 75 mm pier foundation diameter and from Figure 9 to Figure 13 shows the graphical representations of scour depth vs. time for 90 mm pier foundation diameter at different positions of pier foundation with respect to bed level. Scour depths were observed at upstream, downstream, left face, and right face of the compound piers.

The scour depths were observed for two different cases:-

- When the bridge pier foundation top is kept at the sand bed level.
- When the bridge pier foundation top is kept below the sand bed level at 10mm, 20mm, 30mm, and 40mm depth.

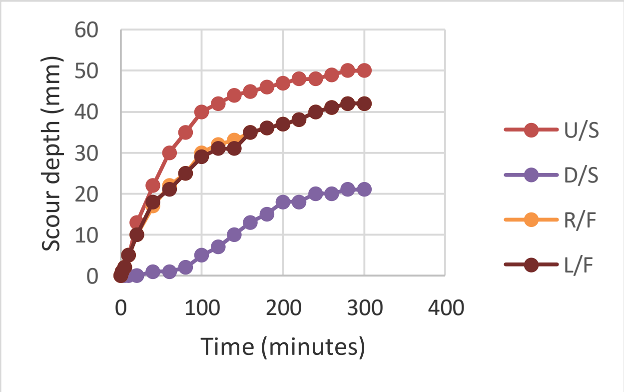

Figure 4. Scour depth vs. time graph for compound circular bridge pier when the foundation top is kept at bed level (model 1)

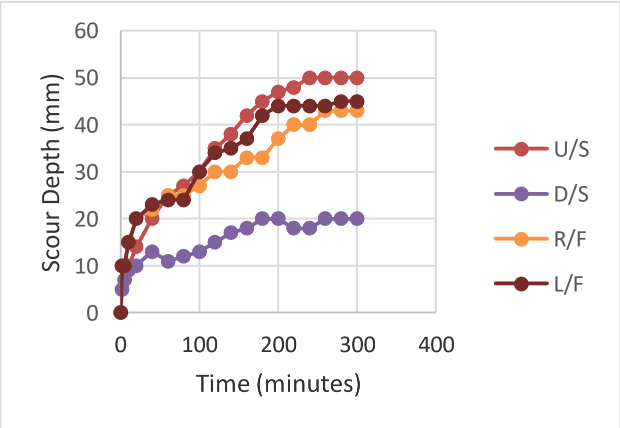

Figure 5. Scour depth vs. time graph for compound circular bridge pier when the foundation top is kept 10mm below the bed level (model 1)

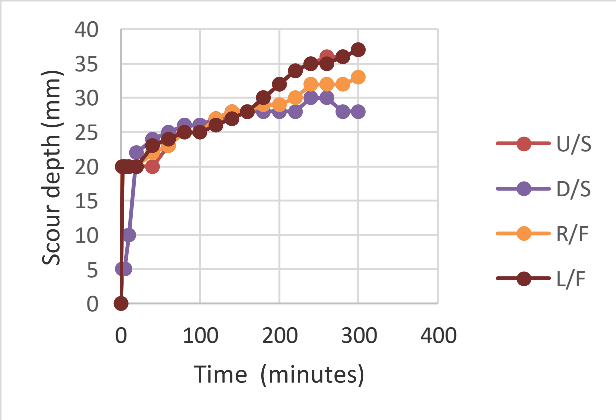

Figure 6. Scour depth vs. time graph for compound circular bridge pier when the foundation top is kept 20mm below the bed level (model 1)

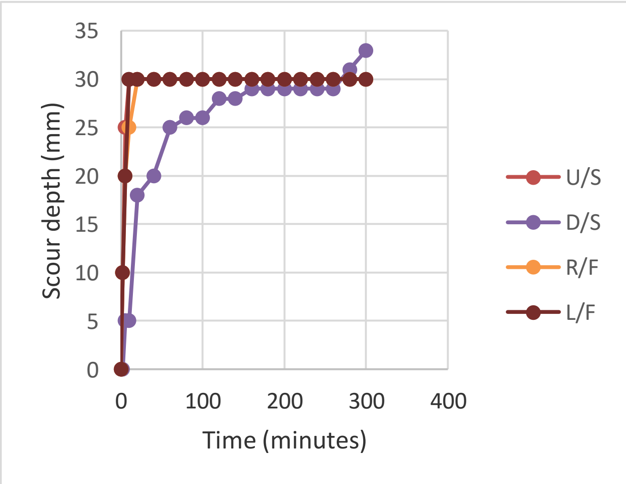

Figure 7. Scour depth vs. time graph for compound circular bridge pier when the foundation top is kept 30mm below the bed level (model 1)

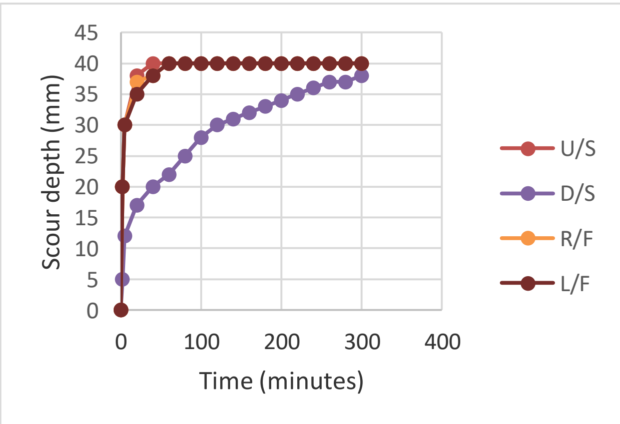

Figure 8. Scour depth vs. time graph for compound circular bridge pier when the foundation top is kept 40mm below the bed level (model 1)

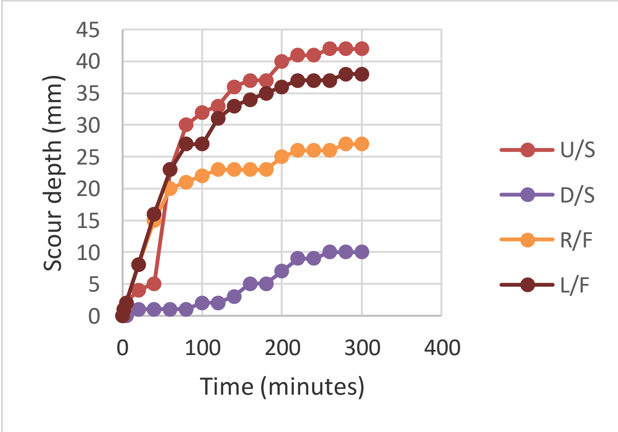

Figure 9. Scour depth vs. time graph for compound circular bridge pier when the foundation top is kept the same as the bed level (model 2)

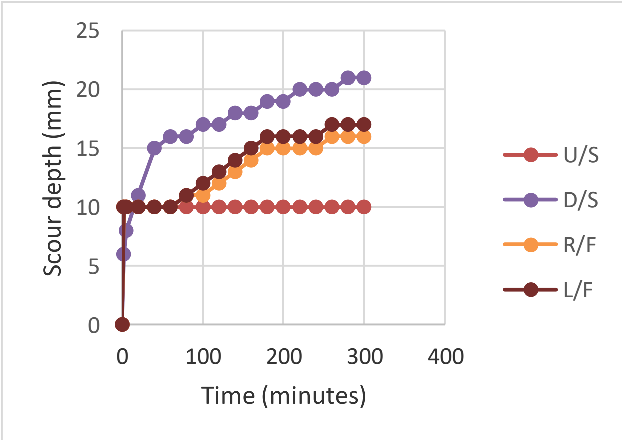

Figure 10. Scour depth vs. time graph for compound circular bridge pier when the foundation top is kept 10mm below the bed level (model 2)

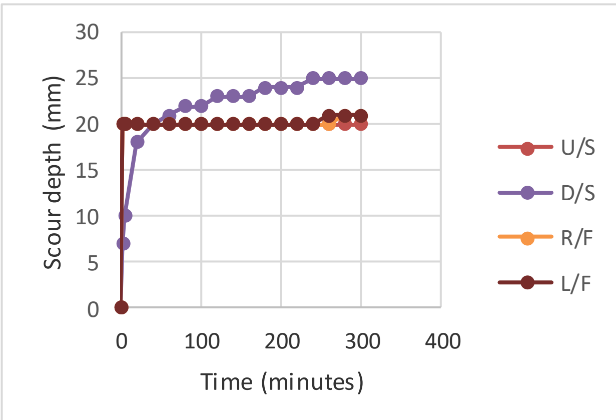

Figure 11. Scour depth vs. time graph for compound circular bridge pier when the foundation top is kept 20mm below the bed level (model 2)

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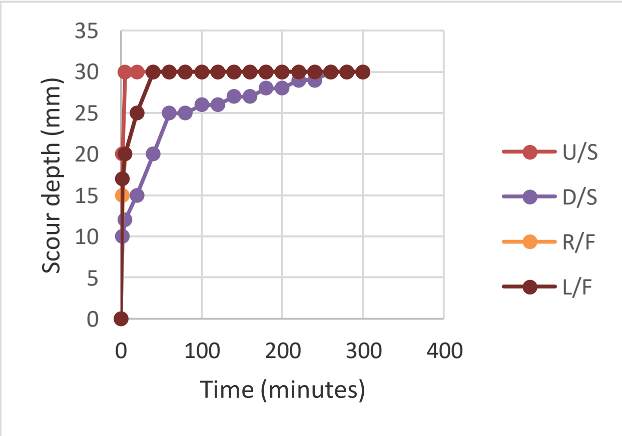

Figure 12 Scour depth vs. time graph for compound circular bridge pier when the foundation top is kept 30mm below the bed level (model 2)

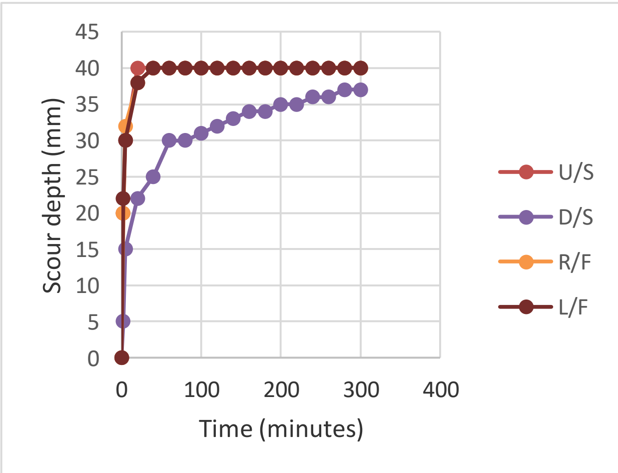

Figure 13 Scour depth vs. time graph for compound circular bridge pier when the foundation top is kept 40mm below the bed level (model 2)

(a)

(b)

(c)

(d)

Figure 14. (a) and (b) The local scour depth during experiment; (c) scour spread after achieving equilibrium depth; (d) scour depth results after achieving equilibrium time (upstream view)

A. Scour depth as a function of foundation top elevation

A graph is plotted for the depth of scour as a function of Y/b for both the models of compound circular bridge pier as shown in Figure 15. The trend in data set showing a decrease in scour depth with an increase in the foundation top elevation till Y/b = 0.9 and then increase for model 1. But for model 2 data set showing an increase in scour depth with an increase in the foundation top elevation till Y/b value of 0.9 and then becomes constant with increase in the foundation top elevation. Scour depth is minimum for Y/b values in the range of 0.6 and 0.9. Table IV gives the values of Y/b and ds/b for present studies.

Table IV. Scour depth as a function of foundation top elevation

Y/b	ds/b (Model 1)	ds/b (Model 2)
0	1.562	1.3125
0.31	1.562	0.656
0.625	1.156	0.781
0.957	1.031	0.9375
1.25	1.25	0.952

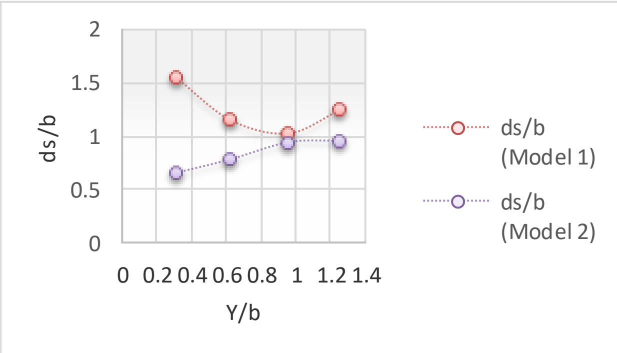

Figure 15. Scour depth as a function of foundation top elevation

In Figure 16 *dsmin* i.e. minimum scour depth are plotted as a function of *b/b** and also the level of *Ymin* at which the minimum scour depth occurs for a particular *b/b** value which is also shown in Figure 16. Table V gives the values of *dsmin/b* and *Ymin/b* for different values of *b/b**.

Table V. Minimum scour depth for different geometries of compound pier

*b/b**	*dsmin/b*	*Ymin/b*
0.426	0.625	0.312
0.355	0.312	0.312

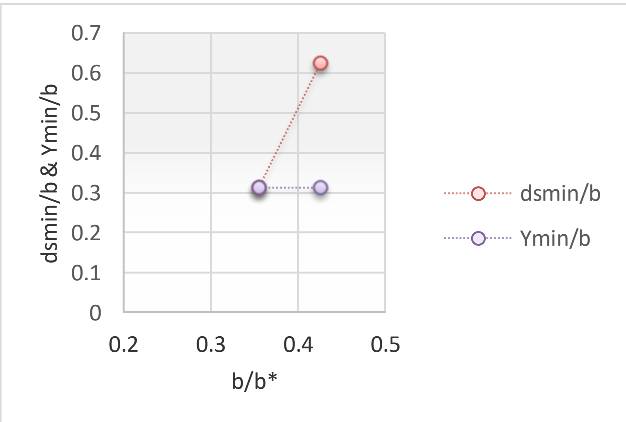

Figure 16. Pier geometry for optimum protection of scour

B. Results and Discussions

The scour depth with respect to time around compound circular bridge piers were measured for the two models having b/ b* ratio as 0.426 and 0.355. The top surface position of the foundation was systematically varied and the same was placed, respectively, the same as sand bed level, 10mm, 20mm, 30mm, and 40mm below the sand bed level. The following results were noticed in the scouring process.

- Figure 4 to Figure 13 shows the graph for the development of scour depth with respect to time for compound circular bridge pier of model 1 and model 2. Rapid scouring could be seen for an initial time period on U/S, L/F, and R/F of the bridge pier as compared to D/S face of the bridge pier which is the effect of the principle horseshoe vortex.
- When the foundation top is kept at a certain depth (10mm, 20mm, 30mm, and 40mm) below the bed level, for an initial time period rapid scouring could be seen on U/S, L/F, and R/F of pier and maximum scour depth could be seen on U/S face of the bridge pier. But when the foundation top is kept at 30mm below the bed level for model 1 and (10mm and 20mm) for model 2, the maximum scour depth could be seen on D/S face of the bridge pier.

For both the models scouring becomes slow and constant after the initial 20-60 minutes and scour depth development also reduces. The scour hole was enlarging in the cross-sectional area and slightly deeper on the downstream side of the bridge pier because continuous scouring could be seen there.

- As the scour depth increases at the downstream side of the bridge pier it gradually finds its way around the L/F and R/F sides of the bridge pier foundation, developing two shallow grooves which meet the upstream side of the bridge pier foundation on the centerline for both the bridge pier models.
- Subsequently, the scour depth hole around the bridge pier foundation increased again due to the vortex formation, the horseshoe vortex enlarges in diameter and deepens the scour depth at the rim of the bridge pier foundation which induces vortex formation there that contributes to the further scour.
- It was observed that the foundation top of the bridge pier is not exposed when the foundation top is kept 40mm below the bed level for model 1 and (30mm and 40mm) for model 2.

With an increase in the diameter of the bridge pier foundation, scour depth reduces because the horseshoe vortex is not able to scour further more due to the enlarged diameter of the foundation top.

- With an increase in the foundation top beneath the bed level there was a decrease in the scour depth in all the models of the compound circular bridge pier, this is due to the fact that the range where the foundation top is beneath the initial level of bed, but above the minimum ds level, the scour hole develops as for the bridge pier alone until the foundation top is exposed when the scour stops.

IV. CONCLUSION

On the basis of the present study following conclusions have been drawn:

- Scour depth depends on the bridge pier geometry and also depends on the shape and size of the bridge pier foundation diameter.
- For the uniform sediment and circular compound bridge pier scour depth depends on top elevation Y of pier footing and foundation diameter ratio b/b*.

- It is observed that the scour depth is maximum when the foundation top is kept the same as the bed level for model 1 and model 2.
- The ratio of scour depth to pier diameter ds/b is minimum for Y/b values ranging from 0.6 to 0.9 value.
- It has been observed that for model 1 there is a decrease in scour depth with an increase in the footing elevation till Y/b = 0.9 value and then after Y/b = 0.9 value scour depth start increasing with an increase in the footing elevation. But for model 2 scour depth increases with an increase in the footing elevation till Y/b values of 0.9 and then scour depth becomes constant with an increase in the footing elevation.
- For model 1 it is observed that the foundation top is exposed when Y i.e. position of pier footing with respect to bed level is kept at (10mm, 20mm, 30mm, and the same as the bed level) therefore, the foundation lies within the vicinity of scour hole. Whereas when the footing elevation is kept at 40mm below the bed level, the top of the footing is not exposed which means footing does not lie in the vicinity of scour hole.
- For model 2 it is observed that the top of the foundation is exposed when Y i.e. position of pier footing with respect to bed level is kept at (10mm, 20mm, and the same as the bed level) therefore, the foundation lies within the vicinity of scour hole. Whereas when the footing elevation is kept at 30mm and 40mm below the bed level the top of the footing is not exposed which means footing does not lie in the vicinity of scour hole.

NOTATIONS

The following symbols have been adopted for use in this paper:-

Q = Discharge [m^3/s];
C_d = Coefficient of discharge [0.61];
g = acceleration due to gravity [m/s^2];
H = Head over a weir [m];
h= Height of weir [m];
V = Approach velocity of flow [m/sec];
A = cross sectional area of flow [m^2];
B = Width of the flume [m];
D = Depth of flow [m];
d_{50} = Mean diameter of particle [mm];
σ_g = Geometric standard deviation
V_c = Critical flow velocity [m/s];
U_{*c} = Critical shear flow velocity [m/s];
b = Pier diameter [mm];
b^* = Pier foundation diameter [mm];
ds = The scour depth [mm];
dsmin = The minimum scour depth [mm];
dsmax = The maximum scour depth [mm];
Y = The footing elevation [mm];
U/S = Upstream face of the bridge pier to the flow;
D/S = Downstream face of the bridge pier to the flow;
R/F = Right face of the bridge pier to the flow;
L/F = Left face of the bridge pier to the flow.

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9. Jyotsna Ramchandra Kore, P.T. Nimbalkar, "Crop water requirement of irrigation scheme selected crops using crop wat 4.0 case study of khadakwasla dam irrigation project," International Journal of Civil Engineering and Technology (IJCIET) , Volume 8, Issue 5, May 2017.
10. Shekhar Kumbhar, P.T. Nimbalkar, "Study of Anantpur community micro irrigation project – Design and preparation of project philosophy," International Journal of Civil Engineering and Technology (IJCIET), Volume 9, Issue 6, June 2018.

Workshop/seminar/conference attended:

1. National conference on Hydraulics and water resources with special Emphasis on "Interlinking of Rivers" A National conference at BVDUCOE Pune, 2006.
2. ISTE Sponsored STTP On "Recent advances in PCT at BVDUCOE Pune, 2006, TTTIR Academic Monitoring Program, B.V.D.U. College of Engineering Pune, 2007 Foundation Problems in Geotechnical Engineering – One Day Workshop.
3. TEQIP II Sponsored Workshop on "Leadership Development" B.V.D.U. College of Engineering, Pune dated 22nd August, 2013.
4. Training Course on "Modeling Techniques for Sediment Transport in Coastal Engineering, Central Water and Power Research Station, Pune during 9th – 10th October 2013.
5. Two days' workshop on Sediment Control in Hydro Power Plants in Himalayan ranges, CW & PRS, Pune on 29 and 30th September 2015.

Extra Activity: Pursuing Ph.D. at NIT Surat, India